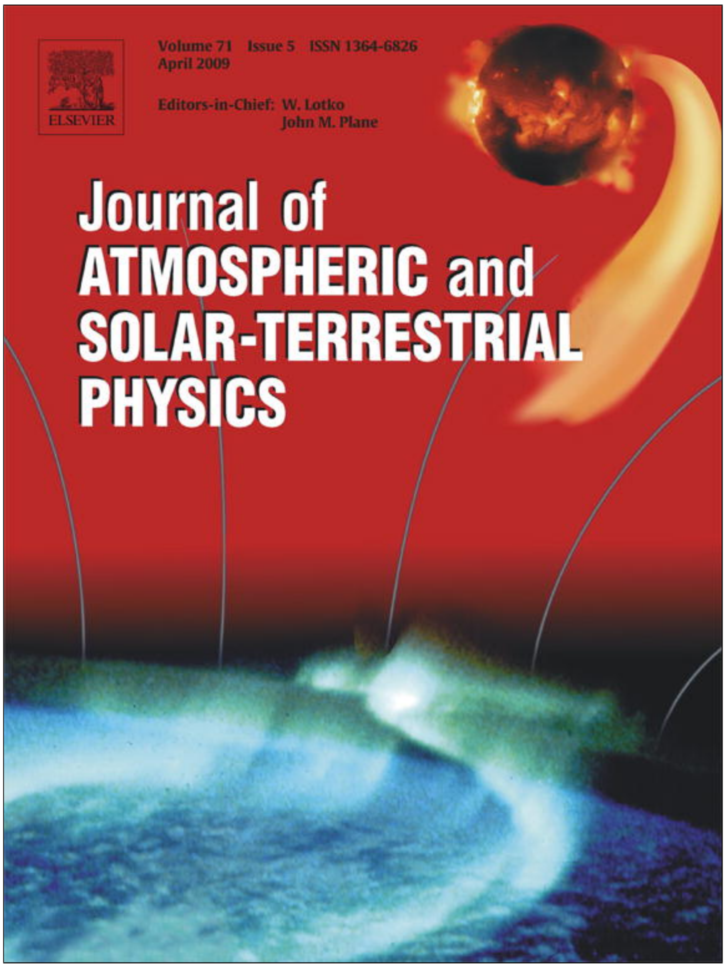
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One-minute rain rate distribution in Nigeria derived from TRMM satellite data

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ABSTRACT

Data from the Tropical Rainfall Measuring Mission (TRMM) satellite sensors, the Microwave Imager (TMI, 3A12 V6) and other satellite sources (3B43 V6) have been used to derive the thunderstorm ratio β, total rain accumulation M, and 1-min rainfall rates, R1min, for 37 stations in Nigeria, for 0.001–1% of an average year, for the period 1998–2006. Results of the rain accumulations from the TRMM satellite (1998–2006) were compared with the data collected from 14 ground stations in Nigeria for the period 1991–2000. The two data sets are reasonably positively correlated, with correlation coefficients varying from 0.64 to 0.99. Deduced 1-min rainfall rates compared fairly well with the previous ground data of Ajayi and Ezekpo (1988. Development of climatic maps of rainfall rate and attenuation for microwave applications in Nigeria. The Nigerian Engineering 23(4), 13–30) with correlation coefficients varying from 0.17 to 0.97 in all 37 stations. The agreement was much better when compared with the International Telecommunications Union Radio communication Study group 3 digital maps with correlation coefficients varying from 0.84 to 0.98 in 23 locations; however there were negative correlation coefficient (of 0.2 in 7 stations) in the Middle Belt and a weak positive coefficient (of 0.09 in 6 stations) in the South South. Regionally the inferred mean annual 1-min rainfall rates are the highest in the South-East region with values between 111 and 125 mm/h throughout the 9 years, followed by the South-South region (105–124 mm/h). The lowest rainfall rate and rainfall accumulation occur in the North-West region (60–86 mm/h) followed, in ascending order, by the North-East (66–95 mm/h) region, the Middle-Belt region (76–102 mm/h) and the South-West region (77–110 mm/h). The present results were also compared with 9 tropical stations around the world and there was positive correlation between the results. The present results will be very useful for satellite rain attenuation modeling in the tropics and subtropical stations around the world.

It is useful to note that one country, particularly one as large as Nigeria, can have significant variations in its rainfall characteristics for a variety of reasons, and this is borne out by the results presented.

1. Introduction

Rain absorbs and scatters significant amounts of radio signal at frequencies well above 10 GHz. Rain can also cause depolarization of radio wave signals. The amount of rainfall (the accumulation) is not as important as the rainfall rate, the signal attenuation and depolarization being proportional to the rainfall rate. Therefore there is the need for reliable rainfall rate data for planning and designing of satellite communications system, management of water resources and to assess the impact of climate change. Rain gauge measurement networks are not as dense or evenly spaced in Nigeria as in the other developed countries like the US and Japan; thus satellite observation of rainfall networks may be the best solution for adequate temporal and spatial coverage of rainfall.

Satellite-based precipitation data can provide very high temporal (3 hourly) and spatial (0.25° latitude by 0.25° longitude grid size) resolutions. Nevertheless, the measurement approach will always lead to a bias in the data (i.e. a large mean error) as well as a random variation about that mean (the stochastic error) and needs to be adjusted to in-situ observations (Barrett et al., 1994; Huffman, 1997; Rudolf et al., 1994). In essence, ground-truth data are needed to calibrate space-borne sensors. Satellites have biases and random errors that are caused by factors such as the sampling frequency, the diurnal cycle of rainfall, the non-uniform field of view of sensors and the uncertainties in the rain retrieval algorithms Bell et al., 1990; Kousky, 1980; Kummerow, 1998; Anagnostou et al., 1999a, 1999b; Chiu et al., 1990, 1999; Chang and Chiu, 1999). In general, rain gauge observations yield relatively accurate point measurements of precipitation but also suffer from sampling error in representing aerial means. They are not available over most ocean and undeveloped land areas (Xie and Arkin, 1995, 1996).

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The Tropical Rainfall Measuring Mission (TRMM), an American–Japanese earth satellite observation mission (launched in November 1997 to an altitude of 350 km) was to provide a better understanding of precipitation structure and heating in the tropical regions of the earth (Simpson et al., 1996). Operating in a non-sun-synchronous orbits, it has an orbital period of 91 min,

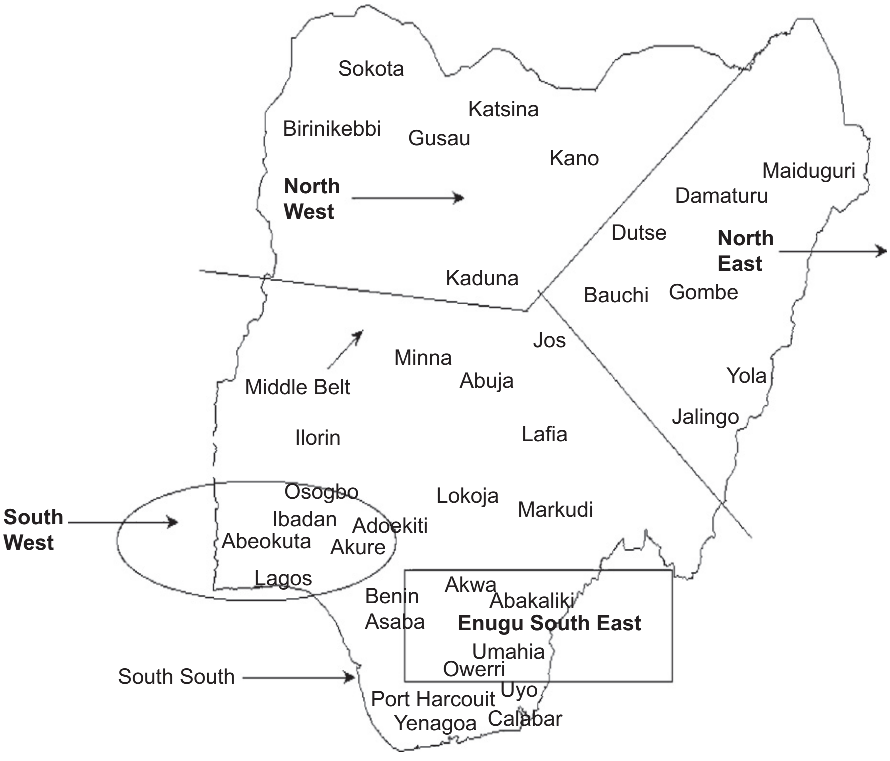

Fig. 1. Map of Nigeria showing the 37 stations used in the study.

Table 1
Seasonal variation of mean precipitation, percentage mean bias error and overall correlation coefficients of TRMM 3B43V6 data with ground data at 14 locations in Nigeria for the period January 1998–December 2000.

Regions/climate	locations	(A)				(B)				$\frac{(A-B)}{A} \times 100$				Overall correlation coefficients of (A) with (B)			
		Ground data Mean precipitation (mm)				TRMM 3B43V6 data Mean precipitation (mm)				Percentage mean bias error							
		DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON	DJF	MAM	JJA	SON
South West	Adoekiti	16.6	187.3	200.7	83.4	12.1	130.6	179.2	146.1	27.1	30.3	10.7	−75.2	0.58	0.93	0.97	0.81
Tropical wet	Ibadan	14.9	90.2	187.7	145.0	14.3	130.9	166.7	152.0	4.0	−45.1	11.2	−4.8	0.57	0.93	0.94	0.99
	Ikeja	14.2	85.0	160.1	167.4	11.5	126.4	178.3	108.4	19.0	−48.7	−11.4	35.2	0.90	0.95	0.99	0.97
South East	Enugu	8.1	147.2	244.5	174.8	23.4	137.2	310.6	152.0	−188.9	6.8	−27.0	13.0	0.75	0.91	0.95	0.99
Tropical wet																	
South South	Calabar	85.9	190.5	387.6	336.2	61.4	217.3	555.3	411.7	28.5	−14.1	−43.3	−22.5	0.91	0.89	0.95	0.99
Tropical wet	Port Harcourt	24.5	176.8	305.7	287.6	70.9	153.8	426.2	374.3	−189.4	13.0	−39.4	−30.1	0.85	0.94	0.98	0.96
	Yenagoa	28.8	131.6	193.1	211.0	76.5	190.3	264.3	333.1	−165.6	−44.6	−36.9	−57.9	0.71	0.92	0.83	0.94
Middle belt	Ilorin	5.6	91.6	206.5	154.6	26.2	104.4	163.2	108.6	−367.9	−14.0	21.0	29.8	0.83	0.90	0.93	0.94
Savanna North	Minna	0.0	45.3	247.1	88.7	6.2	92.1	184.6	98.5	100.0	−103.3	25.3	−11.0	0.56	0.77	0.96	0.87
	Jos	0.0	91.7	211.6	93.3	7.2	82.4	212.2	96.7	100.0	10.1	−0.3	−3.6	0.79	0.90	0.96	0.96
North West	Kaduna	0.0	46.9	217.1	67.7	6.7	41.7	204.6	120.4	100.0	11.1	5.8	−77.8	0.76	0.86	0.97	0.73
Savanna North	Kano	0.0	25.2	363.2	104.1	3.5	5.8	174.2	55.5	100.0	77.0	52.0	46.7	0.75	0.99	0.98	0.99
North East																	
Savanna North	Jalingo	0.0	56.2	204.8	65.7	5.3	87.3	240.6	125.4	100.0	−55.3	−17.5	−90.9	0.76	0.90	0.97	0.96
Semi-arid	Maiduguri	0.0	7.1	181.3	57.4	0.4	11.9	163.1	69.1	100.0	−67.6	10.0	−20.4	1.00	1.00	0.94	0.96

Note: DJF = Dec, Jan, Feb; MAM = Mar, Apr, May; JJA = Jun, Jul, Aug; SON = Sep, Oct, Nov.

making 16 orbits per day, to provide a good coverage of the tropics. TRMM's onboard instruments include the precipitation radar (PR), Microwave Imager (TMI), Visible and Infrared Scanner (VIRS), Cloud and Earth's Radiant Energy System, and Lightning Imaging Sensor. Of these, probably the most prominent is the PR. At the launching stage, TRMM PR was the first space-borne radar that was designed to capture a more comprehensive structure of rainfall than any space-borne sensor before it. It has been producing three-dimensional rainfall data from space in a manner unprecedented by any previous scientific spacecraft. The ground validation sites in Africa for TRMM satellite data are in Congo (−4.0, 16.0) and Conakry (10.0, −14.0) of West Africa.

The main objective of this paper is to report the estimated rainfall rates (for 0.001–0.01% of an average year) for use in estimating rain attenuation of radio wave signals on earth–space paths and to compare these with data measured on the ground (McCarthy et al., 1994b; Moupfouma, 1987; Moupfouma et al., 1990) or predicted by the ITU-R databases (ITU-R P.837-5, 2007). Two TRMM satellite data sets (from 1998 to 2006) were used to retrieve the rainfall accumulation over major state capitals in Nigeria.

2. Data source (rainfall archives)

TRMM data from EOS DAAC NASA Goddard Space Flight Centre, Maryland, US were used. They included:

(a) Monthly TMI rain product (3A12 V6) containing surface, convective and stratiform rain rates in mm/h. As it applies to TRMM satellite, Stratiform rain is a widespread continuous precipitation produced by large-scale ascent due to frontal or topographic lifting or large-scale horizontal air convergence caused by other means, while convective rain is a localized, rapidly changing, showery precipitation produced by cumulus-scale convection in an unstable air. The third type comprises all rain that is not included in these two categories. When bright bands do not exist, rain is classified stratiform. When bright bands do not exist but any value of Z along the range exceeds a predetermined value, rain is classified as convective. When bright bands do not exist and all values of Z along the range are less than the predetermined value, rain is classified as others (Nirala and Cracknell, 2002). The 3A12 V6 data set was based on 1° latitude by 1° longitude spacing.

Table 2
Summary of rain events in Nigeria derived from TRMM 3B43V6 data: [a]January 1998–December 2006.

Regions	State capitals	Total no. of rainy events in 9 yr	Average rain events per year	Average rain accumulation per month (mm)	Average rain total per year (mm)	Total no. of month with rain per year	Dry months with no measurable rain
South West	Abeokuta	2924.0	324.0	92.0	1100.0	8	11, 12
	Adoekiti	3011.0	334.0	104.0	1242.0		12
	Akure	3011.0	334.0	110.0	1314.0		12
	Ibadan	2721.0	302.0	104.0	1245.0		1, 12
	Ikeja	2956.0	328.0	101.0	1217.0		2, 12
	Osogbo	2770.0	307.0	104.0	1245.0		1, 12
South East	Abakaliki	2714.0	302.0	200.0	2394.0	9	1, 2, 12
	Akwa	2919.0	324.0	158.0	1899.0		1, 11, 12
	Enugu	2919.0	324.0	158.0	1899.0		1, 11, 12
	Owerri	3165.0	352.0	200.0	2397.0		12
	Umuahia	3165.0	352.0	200.0	2397.0		12
South South	Asaba	2769.0	308.0	158.0	1900.0	9	1, 11, 12
	Benin	2769.0	311.0	162.0	1948.0		1, 12
	Calabar	3012.0	335.0	312.0	3748.0		1, 12
	Port Harcourt	3165.0	352.0	235.0	2817.0		1
	Uyo	2859.0	318.0	202.0	2429.0		1, 2, 12
	Yenagoa	3105.0	345.0	231.0	2766.0		1, 2, 12
Middle Belt	Abuja	2895.0	322.0	105.0	1258.0	7	11
	Ilorin	3108.0	345.0	94.0	1132.0		11
	Lafia	2679.0	298.0	96.0	1146.0		3, 11, 12
	Lokoja	2590.0	288.0	111.0	1334.0		11, 12
	Markurdi	2404.0	267.0	117.0	1398.0		1, 2 , 3, 11, 12
	Minna	2864.0	318.0	87.0	1049.0		11
	Jos	3196.0	355.0	99.0	1184.0		11, 12
North West	Birini Kebbi	1680.0	187.0	64.0	764.0	4	1, 2 , 3, 11, 12
	Gusau	1176.0	197.0	60.0	721.0		1, 2, 3, 4, 11, 12
	Kaduna	3196.0	355.0	93.0	1112.0		1, 2, 11, 12
	Kano	3075.0	342.0	63.0	754.0		4, 5, 6
	Kastina	1771.0	197.0	50.0	600.0		1, 2, 3, 4, 12
	Sokoto	1379.0	153.0	47.0	564.0		1, 2, 3, 4, 11, 12
North East	Bauchi	2985.0	332.0	72.0	863.0	6	11
	Damaturu	2165.0	241.0	50.0	598.0		1, 2, 3, 4, 11, 12
	Dutse	2743.0	305.0	54.0	649.0		10, 11
	Gombe	2682.0	298.0	63.0	759.0		2, 3, 4
	Jalingo	3106.0	345.0	118.0	1417.0		11
	Maiduguri	2442.0	271.0	54.0	650.0		2, 3, 4
	Yola	3045.0	338.0	86.0	1027.0		11

[a] Note: There was a 3-month satellite signal outage. Total number of months = 105, the numbers 1–12 in column eight mean Jan (1)–Dec (12).

(b) Monthly TRMM and other satellite data sources. Rainfall estimate (3B43 V6) is one of the operational products of TRMM based on rain gauge measurements and satellite estimates of rainfall. The algorithm was developed by the TRMM science team and the data were processed by the TRMM science data and information system. The gridded estimates are on a temporal resolution of 0.25° latitude by 0.25° longitude spacing. The combined data set is based on the concepts of (Huffman et al., 1995) combining precipitation data sets. The TRMM best estimates method is a combination

Table 3
Year to year variations of one-minute rainfall rates (in mm/h) exceeded for 0.01% of an average year derived from TRMM 3B43V6 satellite data: January 1998–December 2006.

Regions	State capitals	Rainfall rates in mm/h									
		1998	1999	2000	2001	2002	2003	2004	2005	2006	Mean
South West	Abeokuta	84	96	89	79	92	88	92	77	87	87
	Adoekiti	98	102	92	87	95	87	86	87	93	92
	Akure	96	107	90	88	92	85	90	91	110	94
	Ibadan	92	110	89	85	93	94	92	85	94	93
	Ikeja	81	89	69	79	79	83	77	81	76	79
	Osogbo	92	110	88	91	95	93	96	87	96	94
South East	Abakaliki	114	131	128	121	133	120	129	123	128	125
	Akwa	102	117	111	120	119	113	102	101	114	111
	Enugu	102	117	111	120	119	113	102	101	114	111
	Owerri	116	134	121	129	129	121	115	122	134	125
	Umuahia	116	134	121	129	129	121	115	122	134	125
South South	Asaba	101	120	115	115	115	101	111	111	123	112
	Benin	102	115	109	110	112	86	99	104	110	105
	Calabar	97	106	110	106	107	100	99	84	136	105
	Port Harcourt	121	124	118	118	120	107	120	101	117	116
	Uyo	125	130	116	130	123	117	120	123	129	124
	Yenagoa	113	134	121	118	124	117	135	128	129	124
Middle Belt	Abuja	102	94	89	94	101	102	87	84	96	94
	Ilorin	83	98	93	90	86	88	93	84	84	89
	Lafia	87	93	84	87	101	91	85	79	96	89
	Lokoja	95	101	86	86	97	92	94	82	102	93
	Markurdi	91	102	95	81	104	97	87	98	96	94
	Minna	84	96	79	86	86	84	76	77	87	84
	Jos	103	85	85	91	96	92	85	88	98	91
North West	Birini kebbi	69	72	55	59	74	72	69	70	66	67
	Gusau	68	69	74	69	67	78	61	64	71	69
	Kaduna	98	89	72	88	81	89	83	80	93	86
	Kano	76	69	68	66	67	76	73	67	71	70
	Kastina	70	69	63	61	57	69	64	68	65	65
	Sokoto	71	64	63	44	67	52	57	64	60	60
North East	Bauchi	92	83	72	84	78	79	66	65	82	78
	Damaturu	71	60	63	59	62	86	60	71	65	66
	Dutse	73	72	67	66	69	80	68	62	70	70
	Gombe	71	70	67	62	71	81	75	68	77	71
	Jalingo	91	92	99	91	86	88	111	89	107	95
	Maiduguri	67	82	63	67	69	68	72	62	63	68
	Yola	81	82	76	77	83	90	91	74	87	82
	max	125	134	128	130	133	121	135	128	125	136
	min	67	60	55	44	57	52	57	62	60	60

Key: Very High (red), High (yellow), Medium (green), Low (blue) of data from the TMI, PR and VIRS with SSM/I, IR and rain gauge data.

3. Data processing

For ease of data analyses in this work, the 37 stations (Fig. 1) in Nigeria have been divided into six distinct regions namely: South West (SW), South East (SE), South South (SS), Middle Belt (MB), North West (NW) and North East (NE). For each of the 37 stations, the thunder storm ratio β was calculated using the method of Rice and Holmberg (1973). The model divided the rainfall into two types to permit the prediction of rainfall rate statistic from the total rainfall accumulation measured in an average year. The two types are termed mode 1 rain (M1) and mode 2 rain (M2). Mode 1 contained the high rainfall rates associated with strong convective activity and thunderstorms. Mode 2 was simply everything else. Therefore, the total average rainfall accumulation M is

$$M = \mathrm{M1} + \mathrm{M2} \quad (\mathrm{mm}) \tag{1a}$$

The ratio of thunderstorm rain accumulation to the total rainfall accumulation, namely

$$\beta = \mathrm{M1}/M \tag{1b}$$

The 1-min rainfall rate was computed using the method developed by Chieko and Yoshio (2002) in which regional climatic parameters such as the thunder storm ratio β were taken into account in the estimation of the 1-min rainfall rate. This model was found to give the best prediction accuracy among the existing models, especially for small percentage of time (0.001–1%), which is important for radio system design. From their result, it was found that the thunderstorm ratio was an important parameter. As results of their analysis, 1-min rain rates for arbitrary percentage of time p (%), R_p (mm/h), can be estimated by using only the average annual total rainfall and the thunderstorm ratio. The model is given by Eqs. (2)–(5) using coefficients a_p, b_p, c_p with $x = \log(p)$. These equations were determined by multiple regression analyses of a databank of rain attenuation on satellite links of 290 data sets from 84 locations in 30 countries and a databank of different integration time rain rates that contains data sets from 54 locations in 23 countries.

$$R_p = a_p M^{b_p} \beta^{c_p} \tag{2}$$

$$\log(a_p) = 0.1574155x^4 + 1.348171x^3 + 3.528175x^2 + 1.479566x - 2.302276 \tag{3}$$

$$b_p = -4.583266 \times 10^{-2}x^4 - 0.4098161x^3 - 1.162387x^2 - 0.8261178x + 0.911857 \tag{4}$$

$$c_p = 2.574688 \times 10^{-2}x^4 + 0.1549031x^3 + 0.1747827x^2 - 0.2846313x + 1.255081 \times 10^{-2} \tag{5}$$

For the computation of the derived 1-min rainfall rates, a program named *Rainrate* was written in Matlab 7.0, which can be called in Microsoft excel as a function, taking input parameters like annual rainfall accumulation M in mm, thunderstorm ratio β and percentage of time unavailability p in %.

3.1. Validation of TRMM data with measured rain gauge data in Nigeria

Rain gauge data from January 1991 to December 2000 were collected for 14 locations for the validation of TRMM data. The TRMM satellite started its mission in November 27 1997; ground data from January 1998 to December 2000 were used to validate the closeness of the TRMM satellite data with the rain gauge data in the selected locations, which cover the entire six regions in Nigeria. Table 1 shows the seasonal variation of mean precipitation, mean bias error and correlation coefficients of TRMM 3B43V6 data with the ground data collected at the National Meteorological Centre Oshodi, Lagos. The results show that TRMM data were positively correlated with the rain gauge data in all the 14 locations. In the SW region, the seasonal correlation coefficients from December to November vary from 0.58 to 0.99, 0.75 to 0.99 in the SE, 0.83 to 0.99 in the SS, 0.56 to 0.96 in the MB, 0.76 to 0.99 in the NW and 0.76 to 0.96 in the NE regions. Table 1 also shows the seasonal mean bias error of TRMM 3B43V6 data with ground data. Mean bias errors greater than +25 mm occurred in March, April and May (MAM) in two locations, Adoekiti and Kano (the end of dry months). During June, July and August, (JJA, the wettest months), mean bias errors less than −25 mm occurred in four locations (tropical wet climate): Calabar, Port Harcourt, Yenagoa and Enugu, while in Kano (a savanna climate) the mean bias error was greater than +25 mm. In September, October and November (SON), seasonal mean bias errors greater than −25 mm occurred in five locations: Adoekeiti, Port Harcourt, Yenagoa, Kaduna and Jalingo. Adeyewa and Nakamura (2003) had observed similar seasonal mean bias error (for latitudes 4–14°N in Africa) of 25–40, 28–53, 38–54 and 35–45 mm for DJF, MAM, JJA and SON, respectively.

Table 4
Statistical summary of 1-min derived rainfall rates exceeding 0.01% of an average year from TRMM 3B43V6 data: Jan 1998–Dec 2006

Regions	State capitals	Mean	Rainfall rate in mm/h standard deviation, σ
South West	Abeokuta	87	6.0
	Adoekiti	92	6.0
	Akure	94	9.0
	Ibadan	93	7.0
	Ikeja	79	5.0
	Osogbo	94	7.0
South East	Abakaliki	125	6.0
	Akwa	111	8.0
	Enugu	111	8.0
	Owerri	125	7.0
	Umuahia	125	7.0
South South	Asaba	112	7.0
	Benin	105	9.0
	Calabar	105	14.0
	Port Harcourt	116	7.0
	Uyo	124	5.0
	Yenagoa	124	8.0
Middle Belt	Abuja	94	7.0
	Ilorin	89	5.0
	Lafia	89	7.0
	Lokoja	93	7.0
	Markurdi	94	7.0
	Minna	84	6.0
	Jos	91	6.0
North West	Birini kebbi	67	6.0
	Gusau	69	5.0
	Kaduna	86	8.0
	Kano	70	4.0
	Kastina	65	4.0
	Sokoto	60	8.0
North East	Bauchi	78	9.0
	Damaturu	66	9.0
	Dutse	70	5.0
	Gombe	71	6.0
	Jalingo	95	9.0
	Maiduguri	68	6.0
	Yola	82	6.0

The worst bias errors (greater than −100 mm) occur in (the driest months) December, January and February (DJF) at 10 stations.

4. Results and discussion

4.1. Nine-year results of rain events as recorded by TRMM satellite at the 37 locations

Table 2 shows the numbers of rain events recorded by TRMM 3B43V6 data set. We have numbered the months as they occur in the calendar year, namely 1 = January and 12 = December. The highest numbers of rainy events averaged over 9 years of measurements (greater than 3000 events) occurred in 13 locations, namely Adoekiti, Akure, Calabar, Yola Kano, Ilorin, Yenagua, Jalingo, Port Harcourt, Owerri, Umahia, Kaduna and Jos. Table 1 shows that the ground data and TRMM 3B43V6 data were positively correlated with each other in all the 37 stations. In Table 2, Jos and Kaduna recorded the highest average rain events of 355 events per year; however the annual rain accumulations were only 1184 and 1112 mm, respectively. Sokoto (in NW) recorded the lowest total numbers of rainy events of 1771 in 9 years and the lowest average rain events of 153 events per year with an annual rain accumulation of 564 mm, as expected for a semi-arid region (Adejuwon et al., 1990). Calabar (in SS region) recorded the highest average rain accumulation of 3748 mm per year as expected for a tropical rain forest (Adejuwon, 2005). TRMM satellite recorded that the SS, SE and SW regions had the highest average rain accumulation, with SS having between 1900 and 3748 mm, followed by SE (1899–2397 mm) and SW (1100–1314 mm). The satellite recorded that the NW region had the lowest average rain total of 564–1112 mm, followed by NE (649–1417 mm) and MB (1049–1398 mm).

The driest month (when no measurable rainfall fell) in 9 years, common to all location in SW and SE regions is December, while for the SS region, December (except Port Harcourt) and January are the driest. In MB, November was the driest month with the exception of Jos. In NW (except Kaduna and Kano) November–April are the driest months; in Kano, April–June were the driest. In the NE region the driest month was November except Gombe and Maiduguri, which had February–April as their driest months.

Furthermore the TRMM satellite revealed about 8 months of rainfall in the SW region (March–October) and about 9 months in

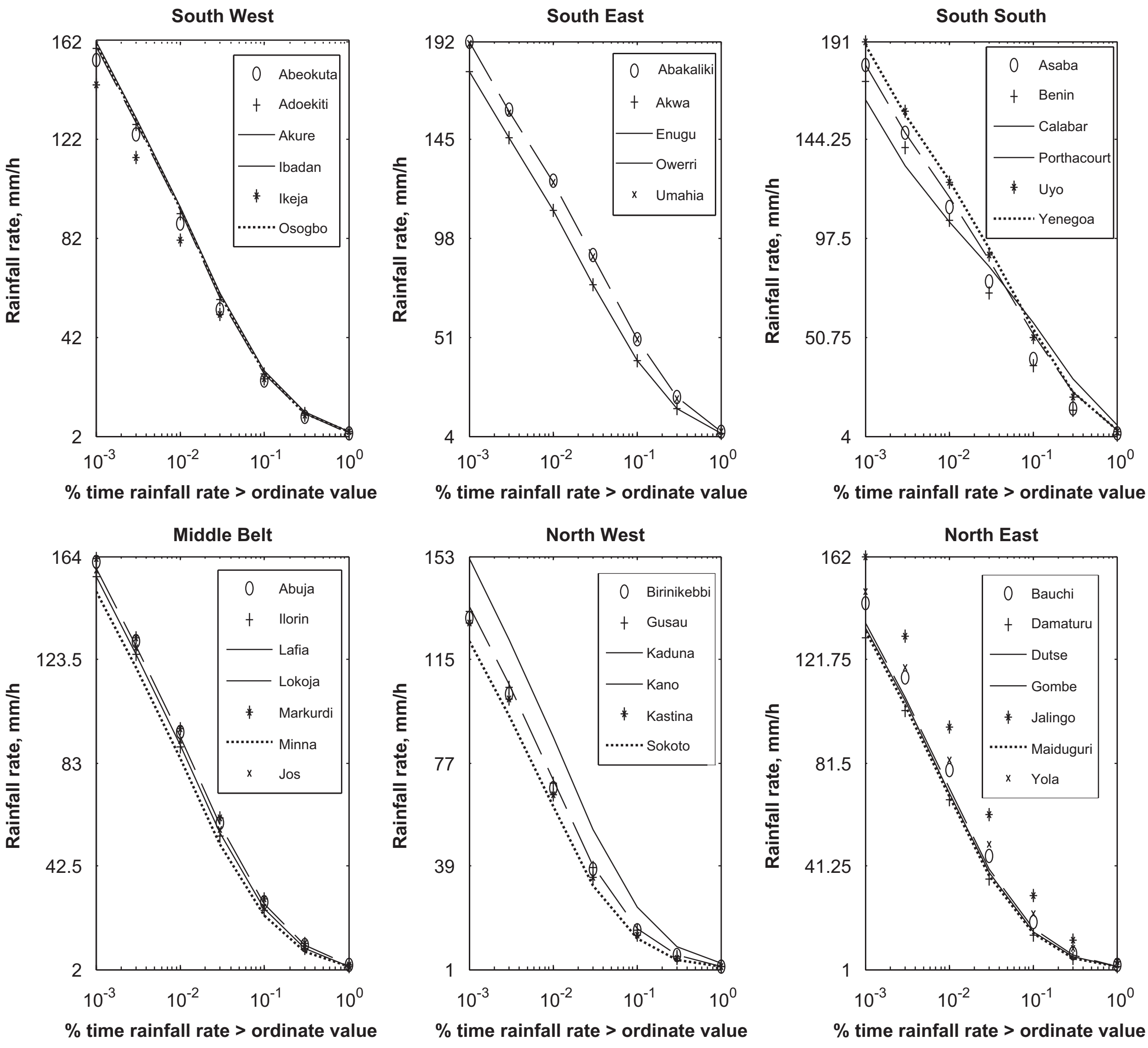

Fig. 2. Cumulative distributions of rainfall rates for the 37 stations in Nigeria.

the SE and SS region (February–October). In the MB region, it was about 7 months of rainfall (April–October), while in the NW and NE regions there were only about 4 months (July–October) and 6 months (May–October) of measurable rainfall, respectively. The results showed further that rainy seasons begin around February–March in the south and April–May in the north, while dry seasons begin in November in all of the 37 stations in Nigeria, where measurements were made (Adejuwon, 2005).

4.2. Year to year variation of the derived 1-min rain rate from TRMM data

Table 3 shows that the results of the year to year variation of 1-min rainfall rates exceeded for 0.01% of the average year for the 37 stations. A four colour chart was used to visualize year to year variations based on the differences between the maximum and minimum rainfall rate data for each year in all of the 37 stations. The results show that the SE region has the highest annual rainfall rates (101–134 mm/h) throughout the 9 years, followed by the SS region (84–134 mm/h). Significantly, the cities Abakaliki, Owerri and Umahia (SE) have the highest mean annual rainfall rate (of 125 mm/h) in 9 years. The lowest rainfall rates and rainfall accumulation occurred in the NW region (44–98 mm/h), followed, in ascending order, by the NE (57–111 mm/h) region, the MB region (76–104 mm/h) and the SW region (76–110 mm/h). Sokoto town in the NW recorded the lowest rain rate of 44 mm/h in 2001 and therefore it had the lowest mean annual rainfall rate of 60 mm/h in 9 years. Table 4 shows the statistical summary of the derived 1-min rainfall rate. The results further show that rainfall rate is highly variable in the SS (Calabar) region with their standard deviation ranging from 5 to 14 mm/h, followed, in descending order, by SW (5–9 mm/h), NW (4–8 mm/h), NE (6–9 mm/h) and MB (5–7 mm/h).

4.3. Cumulative distribution of rainfall rates in the six regions

The average cumulative distributions of rain rate observations for the 9-year period for the six regions are shown in Fig. 2. The rain rates were plotted against percentage of time unavailability from 0.001% to 1%, which correspond to 5.26 min–8.76 h of exceedance of the indicated 1-min rainfall rates in an average year. The cumulative graphs show that the SE (Abakaliki and Umahia) and SS (Uyo) regions have the highest cumulative (of 4–192 mm/h) followed, in descending order, by the MB (Markudi, 2–164 mm/h) and SW (Akure and Osogbo, 2–162 mm/h). The cumulative distribution was the lowest in the NW and NE with values of 1–153 and 1–162 mm/h, respectively.

Table 5
Correlation of the derived 1-min rainfall rates with other works.

Regions	State capitals	ITU-RP SG3 (2008) digital-map-based data (A) mm/h	Present work based on TRMM 3B43V6, data (B) mm/h	Ajayi–Ezekpo contour map data (C) mm/h	Regional correlation coefficient of (A) with (B)	Regional correlation coefficient of (B) with (C)
South West	Abeokuta	90.0	87.0	118.0		
	Adoekiti	93.0	92.0	117.0		
	Akure	95.0	94.0	116.0	0.91	0.17
	Ibadan	96.0	93.0	117.0		
	Ikeja	88.0	79.0	116.0		
	Osogbo	98.0	94.0	117.0		
South East	Abakaliki	106.0	125.0	123.0		
	Akwa	96.0	111.0	122.0		
	Enugu	93.0	111.0	121.0	0.98	0.87
	Owerri	105.0	125.0	125.0		
	Umuahia	104.0	125.0	125.0		
South South	Asaba	99.0	112.0	124.0		
	Benin	100.0	105.0	123.0		
	Calabar	114.0	105.0	125.0		
	Port Harcourt	110.0	116.0	125.0	0.09	0.58
	Uyo	108.0	124.0	125.0		
	Yenagoa	106.0	124.0	125.0		
Middle Belt	Abuja	95.0	94.0	112.0		
	Ilorin	91.0	89.0	114.0		
	Lafia	87.0	89.0	115.0		
	Lokoja	79.0	93.0	118.0	−0.2	0.41
	Markurdi	88.0	94.0	117.0		
	Minna	91.0	84.0	112.0		
	Jos	86.0	91.0	111.0		
North West	Birini kebbi	84.0	67.0	92.0		
	Gusau	88.0	69.0	91.0		
	Kaduna	102.0	86.0	108.0		
	Kano	83.0	70.0	95.0	0.94	0.97
	Kastina	77.0	65.0	85.0		
	Sokoto	79.0	60.0	78.0		
North East	Bauchi	76.0	78.0	105.0		
	Damaturu	75.0	66.0	93.0		
	Dutse	75.0	70.0	94.0		
	Gombe	76.0	71.0	103.0		
	Jalingo	88.0	95.0	102.0	0.84	0.63
	Maiduguri	71.0	68.0	90.0		
	Yola	90.0	82.0	103.0		

Overall correlation coefficients for all sites (A) with (B) = 0.84
Overall correlation coefficients for all sites (B) with (C) = 0.89

4.4. Validation of the derived rainfall rate from TRMM with other works

Table 5 shows the correlation coefficient of the derived rainfall rates with the International Telecommunication Union Radio wave Propagation Study Group 3 digital maps (ITU_RP SG3) and with the work of Ajayi and Ezekpo (1988), which relied on the Rice Holmberg (1973) method to predict 1-min rainfall rate from 30-year rain gauge data for 37 stations in Nigeria. Ajayi and Ezekpo derived a contour map of rainfall rate for Nigeria. The correlation coefficients between this present work and ITU-RP are positive in all regions except in the MB, where there is negative correlation (of 0.20). In Table 5, two outliers in the ITU-RP rain rate data for Lokoja and Minna seem to be the cause of the negative correlation. There is also a weak correlation (0.09) between this work and ITU-RP data only at the SS region, due to low values of ITU-RP rain rate data for Uyo and Yenagoa. This suggests that where local measured data are not available ITU-RP digital map is applicable only in the SW, SE, NW and NE. The correlation coefficient of this work data with those of Ajayi and Ezekpo (1988) is positive in all regions, but there are also two weak correlations (of 0.17) at the SW and (0.41) the MB regions due to lack of resolution between the contour lines of rainfall rates across the two regions. The work of Ajayi and Ezekpo was based on a 30-year data set, while this present work is based on a 9-year data set. Long-term data are expected to smoothen out large variations and thus improve agreement.

Measured 1-min rainfall rates for other tropical and subtropical locations around the world such as Brazil (Migliora et al., 1990), Cameroon (Moupfouma, 1987; Moupfouma et al., 1990), Congo-Brazzaville (Ajayi et al., 1996), Kenya (McCarthy et al., 1994b), Malaysia and Hong Kong (Yusof et al., 1990), India (Sarkar et al., 1992; Sarkar, 1995), USA (Miami –Florida; Sims and Jones, 1973) and Indonesia (Brussaard et al., 1993) were also compared with the results obtained for the 37 locations in Nigeria and the results are presented in Table 6. It is seen from the table that the measured rainfall rates obtained in tropical stations such as India (Shillong, Calcutta and Bombay), Indonesia (Surabaya), Cameroon (Douala), Congo (Brazzaville), Vietnam (Ho Chi Minh) and Australia (Darwin) are comparable with the values derived for tropical wet in the SW, SE and SS part of Nigeria, while the results obtained for subtropical stations in Brazil (Alegre, Fortaleza, Rio de Janeiro, Sao Paulo and Brasilia) are comparable with those of the MB region in Nigeria.

Table 6
Measured 1-min rainfall rates for tropical and sub-tropical locations around the world compared with some tropical and sub-tropical stations in Nigeria for the present study.

Country	Station name	Climatic zone	Measured rainfall rates (mm/h)
India	Tirupati	Sub-tropical	80.0
	New Delhi	Semi-arid	120.0
	Shillong	Tropical	130.0
	Calcutta	Tropical	130.0
	Bombay	Tropical	130.0
Nigeria	Abakaliki	Tropical wet	125.0
	Owerri	Tropical wet	125.0
	Umahia	Tropical wet	125.0
Kenya	Nairobi	Sub-tropical	65.0
Brazil	Gov. Valadares	Sub-tropical	65.0
	Fortaleza	Sub-tropical	82.3
	Rio de Janeiro	Sub-tropical	82.6
	Belem	Sub-tropical	124.3
	Manaus	Sub-tropical	109.3
	Pta. Das Lages	Sub-tropical	104.8
	Brasilia	Sub-tropical	82.7
	Sao Paulo	Sub-tropical	82.9
	P. Alegre	Sub-tropical	90.0
Nigeria	Jos	Sub-tropical	91.0
Nigeria	Markurdi	Sub-tropical	94.0
Indonesia	Surabaya	Tropical	119.6
Cameroon	Douala	Tropical wet	126.0
Nigeria	Yenagoa	Tropical wet	124.0
Congo	Brazzaville	Tropical	104.7
Nigeria	Benin	Tropical wet	105.0
Nigeria	Calabar	Tropical wet	105.0
Vietnam	Ho Chi Minh	Tropical	111.0
Nigeria	Akwa	Tropical wet	111.0
Nigeria	Enugu	Tropical wet	111.0
Australia	Darwin	Tropical	76.6
Nigeria	Ikeja	Tropical wet	79.0
Malaysia	Ipoh	Tropical	250.0
Hong Kong	Hong Kong	Tropical	100.0
USA	Miami-Florida	Tropical	107.0

5. Summary and conclusion

At 0.25° by 0.25° and at 1° by 1° rain gauge and satellite grid spacing we have done 9-year assessments of TRMM 3B43V6 and TRMM TMI 3A12 V6 satellite products, respectively, to derive rain accumulation (both convective and stratiform), thunderstorm ratio and 1-min rain intensities for 37 stations in Nigeria usable in satellite communications. The results show biases in TRMM TMI 3A12 V6 data set as they overestimate both rain accumulation and rainfall rates. In general, the study shows that the 3B43V6 data set closely matches rain gauge data collected for 14 stations from the Nigeria Metrological Centre Oshodi, Lagos, covering 1998–2000. The best agreements with rain gauge data are in the SW, SE, MB and NE part of Nigeria.

Using the TRMM 3B43V6 data set, the result shows that the highest rainfall rates occurred in SE and SS regions, with utmost peaks in the towns of Abakaliki, Owerri and Umahia of 125 mm/h. Using the TRMM 3B43V6 the highest rain accumulation of 3748 mm occurred in Calabar, SS, and the lowest accumulation of 564 mm and rain rate of 60 mm/h occurred in Sokoto, NW. The results have been validated with three other sources; the ITU-RP SG3 digital maps shows good agreement with our results, while the work of Ajayi and Ezekpo (1988) agrees with this present study only at SE, SS, NW and NE regions. Finally, the results obtained show very good agreement with other tropical and subtropical stations around the world.

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